NO CONCRETE IS SUSTAINABLE WITHOUT BEING DURABLE!

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Abstract

Sustainability of concrete is a hot topic nowadays, not only in research but also in practice. The production of Portland clinker is responsible for a significant amount of CO_2-production worldwide. Partial replacement of Portland cement by supplementary cementitious materials should indeed be encouraged. A win-win situation can be obtained by implementing waste materials in concrete, reducing the cement content and avoiding huge amounts of waste disposal. However, no concrete structure can be sustainable without being durable. Even while having an excellent carbon footprint performance per unit of volume, it could be prone to a more accelerated degradation under severe environmental conditions, needing earlier repair or replacement, and thus increasing the cumulated carbon footprint calculated over the entire service life. Performance of alternative concrete mixtures should not only be checked in terms of strength classes, but also in terms of durability performance. It is shown in this paper that alternative mixes with similar strength as a reference mix can show inferior durability performance. As a consequence, sustainability comparisons based on equal strength considerations can be misleading towards the real sustainability over the entire service life of a concrete structure.

1 INTRODUCTION

In Wikipedia, a good description can be found on **sustainability**. *The word sustainability is derived from the Latin sustinere (tenere, to hold; sus, up). Dictionaries provide more than ten meanings for sustain, the main ones being to "maintain", "support", or "endure". However, since the 1980s sustainability has been used more in the sense of human sustainability on planet Earth and this has resulted in the most widely quoted definition of sustainability as a part of the concept sustainable development, that of the Brundtland Commission of the United Nations on March 20, 1987: "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* [1].

Contrary to sustainability, **durability** is not that well explained in Wikipedia. *Durability is the ability to endure. It can refer to: Durable goods, goods with a long usable life in economics; Durability (database systems), one of the ACID properties; In safety and technology: Dust resistant, Fire resistant, Rot-proof, Rustproof, Thermal resistant; Impact resistant; Waterproof* [2].

Durability as well as sustainability is thus referred to as a property or ability to endure. However, sustainability clearly involves also aspects of 'preservation', not compromising future generations. Nevertheless, a lot of confusion exists while discussing sustainability and durability. To many, sustainability and durability are synonyms, or at least do mean something very similar. In some languages there is not even a possibility to make a distinction between sustainability and durability, as only one word exists to translate both (e.g. 'Duurzaamheid' in Dutch). On internet forums, some people do raise the question "*What is the difference between sustainability and durability?*" hoping to get some better guidance [3]. However, only one short answer seems to be added: "*Sustainability is something's ability to last. Often, the durable things are able to sustain longer because they are tougher, more hardy, built to last.*" Unfortunately, this answer is also not very clear, and seems to relate the two words to 'the ability to last' or 'sustain'. The good point, although somewhat hidden, is the statement that *durable things are able to sustain longer*, which can be interpreted as a statement that durability is part of sustainability (although it is not clear whether this is what was meant to be said within the reply given on the forum). However, as defined by the Brundtland Commission, sustainability is about more than just sustaining or lasting for a long time.

Along these lines, a good opinion has been published by Peter Yost in the Magazine of Sustainable Design in 2009: "Sustainability requires durability!" [4]. The strong title of his opinion is nicely illustrated by the statement: "*If you double the life of a building, no matter what the building is made of, you halve the environmental impact of its construction*". He explains that the search for energy saving has led to increased moisture problems in buildings, leading to mold growth, rot, corrosion, air-quality problems and even structural failures. He concludes: "*I am not saying we need to back off on the energy efficiency of our buildings: green buildings absolutely need to be energy misers. But to be green and durable and energy efficient, we need a new mantra: Manage energy and moisture with equal intensity*". Peter Yost is astonished to see "*that most versions of LEED are silent on the critical matter of durability and its dependence on the relationship between energy and moisture control*".

A similar opinion has been published by Eric Wilson in 2011: "*Durability is the Key to Sustainability*" [5]. "*Goods that need replacing every few years, what is known as planned obsolescence, deals a serious blow to the goals of sustainability. When a poorly made object fails, ends up in the waste stream, and leads a consumer to purchase a new widget, there are environmental ramifications for the planet and economic ones for the individual.*"

In the context of concrete structures, it is clear that technical durability is a prerequisite for environmental sustainability. Technical durability can be seen as the resistance to degradation processes [6], while environmental sustainability is – following the Brundtland Commission – linked to the preservation of natural sources and limitation of waste etc. Unfortunately, sustainability of concrete is often limited to carbon footprint per cubic meter of concrete, or carbon footprint to build a structure. However, when a cubic meter of concrete with reduced carbon footprint needs to be replaced much sooner due to a reduced resistance to degradation processes, the environmental benefit can be totally lost or even become negative. A better approach is to perform LCA analysis, duly considering the technical durability of the concrete. In this respect, another common simplification with potential negative consequences is the (erroneous) idea that concrete strength is fully determining the concrete durability. Nevertheless, two different concretes with equal strength do not necessarily have the same technical durability. These aspects will be illustrated further on in this paper.

2 STRENGTH VERSUS DURABILITY

Many standards, including the European concrete code EN 206-1, consider three important parameters in order to guarantee durable concrete structures: water/cement ratio, cement content, and strength. Is has been illustrated previously that each of these parameters can be criticized [7]. As an example of the debatable correlation between concrete strength and durability, Figure 1 shows the carbonation depth after 50 years of exposure to a natural environment for 14 different concrete compositions. The results have been obtained for limestone filler based self-compacting concrete with different cement and limestone filler content, with different water/cement ratio, with different cement/powder ratio, and with different strength class [8]. The carbonation depths after 50 years have been estimated based on experimentally obtained diffusion coefficients.

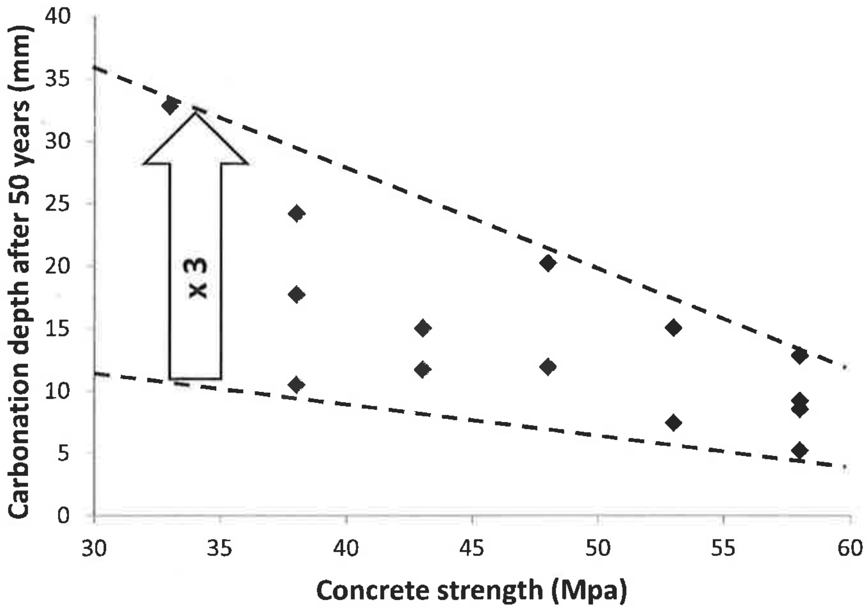

Figure 1: Carbonation depth after 50 years of 14 different SCC mixtures as a function of 28 days' concrete strength.

While limestone filler is accelerating the hydration of Portland clinker due to improved nucleation possibilities, it is not chemically active (except for a minor percentage which could be chemically active in the formation of carboaluminates) [9-11]. In this way, limestone filler improves the strength development, while the improvement by limestone filler of the pore structure and the long term durability performance is not always of the same degree [12]. In ternary blends however, there could be additional synergetic effects between limestone filler and the aluminate phase of a third powder, e.g. slag, fly ash or calcined clay, leading to improved microstructural properties [13,14]. As the effect of addition of powders can be manifold (chemical, physical, filler, dilution) [15], the correlations between simple mix design parameters, strength and durability are not always straightforward. In the example of Figure 1, the difference in mix design is leading to a difference by a factor of three in carbonation depth for concretes having similar strength.

Following typical Fickian diffusion laws, increasing the CO_2 diffusion coefficient by a factor of three is leading to a reduction of the time to reach a certain carbonation depth by a factor of nine! In case the service life of a structure is defined as the time needed for reinforcement steel to be depassivated by carbonation, the service life could thus be reduced by a factor of nine when relying on strength alone as a durability indicator for alternative "sustainable" concrete compositions!

This is illustrated in Figure 2 for the case of a structure with concrete cover 20 mm and intended service life of 50 years. Due to the insufficient technical durability (insufficient resistance against carbonation, with three times higher carbon diffusion coefficient), the alternative composition with similar strength, and which at the same time might have a considerably lower carbon footprint per cubic meter of concrete, will in that case not result in a more sustainable solution!

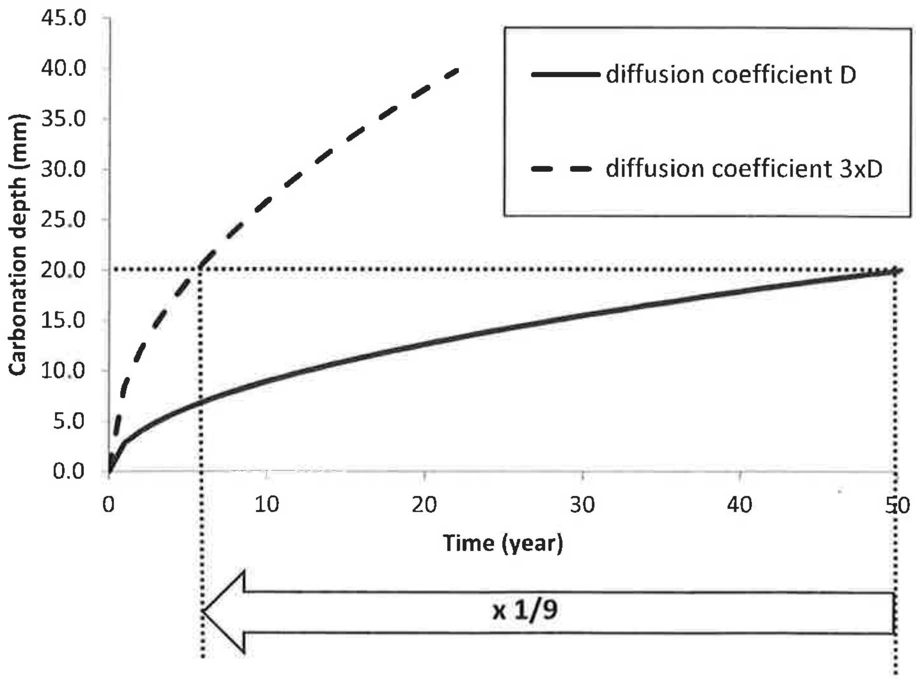

Figure 2: Effect of a tripled diffusion coefficient on the service life (time needed to reach a carbonation depth of 20 mm), following Fick's diffusion law.

In spite of the clear message of manifold trivial examples similar to the one given in Figures 1 and 2, many research papers in international journals only focus on concrete strength when reporting studies showing the feasibility to develop eco-friendly, sustainable mixtures, typically implementing alternative waste materials. Some simplistic reasoning can sometimes be found in these kind of papers. On the one hand, while calculating or estimating the carbon footprint of a cubic meter of concrete, no footprint is considered for the waste materials "*as they are available anyway, and should be landfilled otherwise*". This is not fair, as some of these waste materials are resulting from a polluting industry, e.g. coal power plants. On the other hand, they consider the alternative concrete as sufficient when reaching similar strength values as needed for the reference concretes, implicitly accepting that "*same strength will guarantee same durability performance*", which of course is not valid at all.

3 DURABILITY VERSUS SUSTAINABILITY

As shown before, wrong choices could reduce the service life of the resulting concrete structure by a factor of nine. In literature, the carbon footprint of alternative 'green' mixtures is typically 30% to 60% lower in comparison with reference mixtures. Even keeping only one third of the carbon footprint per cubic meter of concrete, a reduced service life by a factor of nine still means a net increase of the environmental loading by a factor of three in view of a predefined service life (e.g. 50 years), as illustrated in Figure 3. A concrete mixture with a reduced carbon footprint will not lead to sustainable solutions when the concrete does not prove to be durable!

In order to make a reliable evaluation of the 'green' character of a concrete structure with alternative binder systems, a fair analysis has to be made, duly considering the technical durability performance of the 'green' concrete, and not merely the carbon footprint per cubic meter of concrete. In literature, good examples can be found on how to evaluate the real environmental impact of 'green' concretes, based on a detailed life cycle assessment (LCA). Based on literature review and theoretical calculations, Van den Heede and De Belie [16] conclude the following: "*The adopted functional unit for which the environmental impact is calculated, influences the outcome significantly. When comparing different concrete compositions, this unit should incorporate differences in strength, durability and service life. Hence, a cradle-to-grave or modified cradle-to-gate approach is advised as system boundary. When using industrial by-products as cement replacing material in 'green' concrete, an economical allocation of impacts is recommended.*"

One of the major pitfalls, is to blindly rely on similar concrete strength. This misconception is still too widely spread within concrete practice. The erroneous idea saying that "*when it is strong enough, it is durable enough*", is getting more and more risk-full when considering alternative 'green' binder systems. While traditionally, strength is the first and most important concrete property to be considered, a new approach should be followed in which "strength follows durability". It should first (or at least simultaneously) be checked how the 'green' binders should be defined in order to be technically durable. The structural design should afterwards be based on the resulting strength values. This of course raises the question on how to check the durability of alternative 'green' concretes.

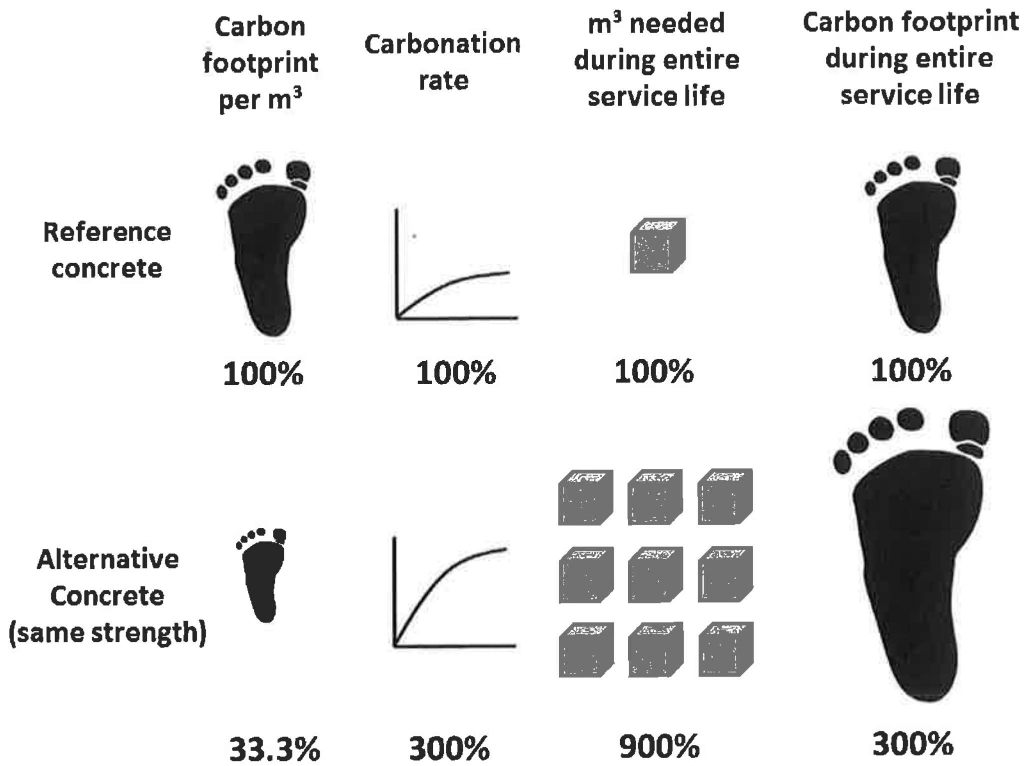

Figure 3: Combined effect of carbon footprint per m^3 of concrete and increased carbonation rate on the carbon footprint during the entire service life.

4 HOW TO EVALUATE DURABILITY?

Current standards, such as the European EN 206, consider durability performance following 'deemed to satisfy' rules. Mainly based on long-term practical experience, minimum cement contents and maximum water/cement ratios are defined in order to obtain durable structures. This approach is practical and is quite reliable in case of well-known traditional binder systems (e.g. based on Portland cement or blast furnace slag cement), at least, on the condition that the casting, placing and curing of the concrete is also following the state-of-the-art rules.

For alternative binder systems, the European Standard defines the ECPC-concept (Equivalent Concrete Performance Concept). Following this concept, the durability performance of an alternative concrete has to be experimentally verified and compared with the durability performance of a well-accepted reference composition. Although the European Standard is not providing detailed prescriptions for the application of this ECPC-concept, some countries have adopted local standards giving more details, as is e.g. the case for Belgium with the Standard NBN B15-100 [7]. The ECPC-concept is considered to be more promising than the traditional k-value concept [17].

A better solution would be to define absolute durability performance criteria, so that the durability performance of alternative concrete compositions can be directly verified without the need of performing comparative tests with reference mixes. The absolute durability performance could be estimated in a non-destructive way on site, on a finalized concrete structure, by special test methods, and following well-defined durability indicators [18,19]. This is a most-promising approach which needs to be further developed.

5 CONCLUSIONS

- Based on available test results for alternative concretes based on blended binders containing alternative materials, it is illustrated that the technical durability of the concrete can be very variable even when the concrete has similar strength.
- For the case of carbonation, based on Fickian diffusion, it is shown that the service life of a concrete structure could be significantly shortened in case of alternative binder systems, even when having similar strength.
- It is further illustrated that the carbon footprint of the concrete structure over the entire service life can be substantially higher in case of reduced technical durability, even if the carbon footprint per cubic meter of concrete is significantly lower.
- As a main conclusion it can be stated that the sustainability of concrete structures should be carefully investigated by duly considering the technical durability of the structurer. New approaches are available, including the ECPC-concept (Equivalent Concrete Performance Concept) and the concept of durability indicators.
- No concrete can be sustainable without being technically durable!

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